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Improved Real-Scale Fire Measurements Having Meaningful Uncertainty Limits

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Abstract

The National Institute of Standards and Technology has undertaken a long-term effort designed to improve our ability to make experimental measurements having quantifiable uncertainties in real-scale fire environments. The adopted approach has two components. The first focuses on quantifying the uncertainties associated with existing techniques commonly employed to characterize real-scale fire environments. Measurements considered thus far include gas temperature using thermocouples, smoke mass concentration using optical extinction, rate of heat release using the NIST furniture calorimeter, and radiative and total heat transfer using heat flux gauges. The measurement of smoke mass concentration is discussed in some detail as an example of how a measurement approach can be modified to provide improved information while at the same time providing reliable estimates of the uncertainty. The second component is centered on the development of new approaches for measurements in fire environments which offer both improved measurement capability and quantification of uncertainties. An effort to combine near-infrared laser diode absorption spectroscopy with fiber optic coupling for local time-resolved measurements of carbon monoxide concentration in fire environments is discussed briefly.

1. Introduction

Man's existence on Earth is intimately tied to fire behavior both through the harnessing of combustion to perform useful functions and through the harmful effects of unwanted fire. To this day, unwanted fire continues to present severe challenges to modern societies. Death, injury, and personal property loss still occur with a distressingly high frequency, while property losses and the costs associated with fire prevention, fighting, and insurance represent significant fractions of developed countries' overall economies. Despite decades of sustained study and considerable progress, a complete understanding of the behavior of unwanted fires and an ability to predict their behaviors has remained elusive. One needs only to consider current capabilities for predicting the growth and effects of a fire in an arbitrary built environment to confirm this conclusion. This lack of understanding is due to the complexity of fire which involves interactions between physical/chemical processes which are difficult to quantify in the absence of any interactions. These processes include pyrolysis of solid fuels, radiative and convective heat transfer, combustion and soot formation, and mixing and reaction in turbulent flows.

The complicated nature of fire behavior has precluded developing an understanding based on first principles and has resulted in an emphasis on experimental characterization of fire behavior, which then serves as the basis for the development of the engineering correlations and fire models used for practical fire protection engineering. Thus experimental fire characterization, and particularly real-scale fire experiments, are central to the development of predictive models for fire growth and effects. The need for such models has become even more urgent with the shift in emphasis in many industrial countries from prescriptive codes (typically developed as responses to historical fire results) to performance-based codes which attempt to provide a specified level of safety through effective engineering based on understanding of fire behavior.

The experimental measurements required to characterize fire behavior are typically made in extremely harsh environments using instrumentation which is subject to errors of various kinds. Historically, the uncertainties associated with fire measurements have not been a focus of attention. Results have typically been reported with little or no discussion of uncertainty. This approach is inconsistent with modern experimental measurement practice which specifies that a quantitative result is incomplete unless it is accompanied by an estimate for its uncertainty and an account of how it was estimated.[1] A specification of the uncertainty is required by anyone utilizing the results, whether it be for model development or some other purpose.

As a result of the above considerations, the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has initiated a long-term research effort with the ultimate goal of providing quantitative estimates for the uncertainties associated with experimental measurements recorded during real-scale fire tests. The following summarizes our progress to date.

2. Approach and Fire Diagnostics Considered

The goal of this research effort is to improve the capabilities of BFRL and the general fire community for quantitatively characterizing fire behavior using experimental measurement techniques having reliable estimates of accuracy and precision. We have chosen to focus on measurements typically performed in the NIST large-scale fire test facility.

The project has two components. The first considers the uncertainties associated with existing measurement techniques employed during NIST real-scale fire tests. In addition to providing the means to estimate the uncertainty in a particular type of measurement, an additional focus is identifying easily implemented approaches for limiting the uncertainties associated with a measurement and extending the usefulness of the technique.

The actual fire diagnostics chosen for characterization have been selected based on interviews with NIST staff and outside fire researchers. Important criteria include the importance of the technique to fire research and the relative level of uncertainty associated with the measurement. The goal is to consider five such fire diagnostics during the course of the project. Currently, four diagnostics have received attention. These include thermocouple measurements of gas temperature, measurements of smoke mass concentration by optical attenuation in the furniture calorimeter, heat release rate measurements using the furniture calorimeter, and measurements of radiative and total heat transfer using heat-flux gauges.

The second component of the effort is the development of a new experimental technique for characterizing the environment in real-scale fire tests. Based on a need for an approach for time-and spatially-resolved in-situ measurements of gas composition, this component is focusing on the development of fiber optic coupled, near-infrared tunable diode laser absorption for concentration measurements. A number of fire species should be measurable using this approach.

Analytical measurements based on the absorption of near-infrared tunable laser radiation have been undergoing rapid development during the past few years.[2] A major driver has been the extensive development of these lasers by the communications industry. As a result, well characterized, reasonably priced tunable diode lasers are commercially available over extensive spectral ranges centered around 1.31 μm and 1.55 μm. This is particularly true in the 1.55 μm region where the implementation of wavelength division multiplexing, in which several different wavelengths are utilized simultaneously for communication purposes, has increased the availability of lasers over the 1.45 μm to 1.65 μm range. Lasers operating at other wavelengths are also available, but are not as well developed and tend to be more costly. Very efficient and reasonably priced fiber optics have also been developed for transmitting the communication wavelengths over large distances. Such fibers can be used for transporting a laser beam to and from an observation region within a fire environment. Absorption measurements are inherently line-of-sight, but by using a "throw and catch" configuration in which the laser beam is transmitted between fibers through a short open space, spatial resolution on the order of a few cm can be obtained. The ability to multiplex multiple lasers onto a single fiber opens the possibility of measuring concentrations for several species, and even temperature, simultaneously.

Absorption transitions in the near-infrared for most molecules are typically overtone and combination bands of the fundamental transitions which occur in the mid-infrared. As a result, the absorption coefficients tend to be small, and it becomes necessary to detect very small absorption signals when operating in the near-infrared. Techniques based on wavelength modulation and phase sensitive detection are often used to record the small absorption signals, but the signal-to-noise ratios of the measurements still generally limit minimum detectable concentrations. The current investigation is aimed at determining whether or not sufficient signal-to-noise ratios can be obtained in fire environments to allow meaningful concentration measurements of fire species. The initial target species is carbon monoxide. Laboratory investigations are being performed to assess our capability to measure carbon monoxide with sufficient spatial and temporal resolution to justify further development of the approach.

3. Summary of Progress To Date

A number of BFRL investigators have been involved in this effort. Table 1 lists their last names. In this section brief summaries are provided for each of the topic areas of the overall effort. The following section describes progress on the Smoke Meter study in more detail.

3.1 Thermocouple Measurements

Measurements were carried out in a 40%-scale model of a standard room in order to investigate uncertainties associated with thermocouple measurements of gas temperatures in fire environments. Temperatures recorded by bare-bead thermocouples typical of those used in BFRL

Table 1. BFRL Researchers Involved in the Fire Diagnostics Study

TOPIC	BFRL RESEARCHERS
Thermocouples	Pitts, Peacock, Blevins, Johnsson, Reneke, Braun, Fernandez
Smoke Measurement	Mulholland, Putorti, Johnsson, Fernandez, Shear
Furniture Calorimeter	Steckler, Johnsson, Pitts
Heat Flux	Bryant, Womeldorf, Johnsson, Blevins, Ohlemiller, Pitts
Near-IR Diode Laser	Blevins, Johnsson, Peterson, Fernandez

fire tests were compared with measurements recorded with aspirated thermocouples as well as with those for a group of closely spaced variable-diameter bare-bead thermocouples. The results of this investigations were summarized at the last UJNR meeting.[3] Briefly, thermocouple gas temperature measurements were found to have significant errors due to radiative heat transfer. The largest relative errors for bare-bead thermocouples were for measurements of low temperature gases in which the thermocouple was subject to radiation from heated surroundings and gases. Temperature errors for thermocouples located in high temperature gases which could radiate to cooler surrounding were typically significant, but relatively smaller than for the former case. Aspirated thermocouples were shown to record temperatures which were less sensitive to the effects of radiation, but, contrary to ASTM recommendations,[4] still had significant systematic errors. A model for the response of bare-bead, single-shield aspirated, and double-shield aspirated thermocouples predicted behaviors which were in qualitative agreement with the experimental findings.[5] Attempts to correct for radiation effects by extrapolating measurements for a series of variable-diameter thermocouples to zero diameter were not successful. Measurements recorded with thermocouples much smaller than typically used for fire testing indicated that the limited time response of thermocouples routinely used in fire testing can lead to very large instantaneous errors in fire environments where temperature fluctuates rapidly.

3.2 Smoke Meter Measurements

The results of this part of the effort are summarized in somewhat greater detail in the following section as a demonstration of how existing fire diagnostics can be improved as well as how levels of uncertainty can be quantified for fire measurements.

3.3 Rate of Heat Release Using the Furniture Calorimeter

The NIST furniture calorimeter is a device based on oxygen depletion which is used to measure heat release rate for fires falling in the 50 to 500 kW range.[6] It is similar to the more widely used cone calorimeter, but there is no source of radiative heating. The furniture calorimeter consists of a hood which captures combustion gases and an exhaust duct where the heat release rate measurements are made. The purpose of this investigation is to provide a quantitative analysis of the uncertainty in the heat release rate measurements. A similar analysis for the standard cone calorimeter has recently been published.[7]

A number of approaches having varying levels of sophistication are available to calculate heat release rate using oxygen depletion that depend on which species concentrations are measured in the effluent gases. For the furniture calorimeter, the stack gases are extracted and dried. Various instruments are then used to record oxygen, carbon monoxide, and carbon dioxide concentrations as functions of time. Other measurements which are required are the pressure drop associated with a bi-directional probe in the duct and the local gas temperature as determined by thermocouple. The latter two measurements are used to calculate the mass flow rate within the duct. Janssens has discussed the appropriate equations [see his Eq. (26) and associated Eqs. (5), (12), and (21)] to use when concentrations for these three gases are available.[8]

A detailed propagation of error analysis has been performed to identify how the uncertainties for the individual measurements influence the overall uncertainty associated with the heat release rate measurement. A series of tests using fires of various sizes has been performed to characterize the individual uncertainties of the various type of measurements required for the rate of heat release calculation. The results are currently being analyzed. They will be used along with the uncertainty propagation analysis to complete the uncertainty analysis for the furniture calorimeter heat release rate measurement.

3.4 Heat Flux Measurements

This part of the project was initiated during the current funding cycle. Initial efforts are focused on the identification of current applications of heat flux gauges within BFRL and the potential uncertainties for these measurements. Applications range from calibrations of heat flux levels in standard tests such as the cone calorimeter and LIFT, to measurements of heat flux at positions exposed to thermal radiation from a fire, to the measurement of total heat flux to a fuel surface during flame spread and burning. The latter environment is the most difficult in which to make heat flux measurements and to estimate the uncertainties associated with the measurement. At the same time, it is perhaps the most important since an understanding of fire spread is a prerequisite for predicting fire behavior. This particular scenario has been selected as a test case for developing the approaches necessary to estimate uncertainties in heat flux measurements.

4. Smoke Meter Measurements

The smoke (here meaning the particulate generated by a fire) yield, defined as the kilograms of smoke produced during the burning of a kilogram of fuel, is a crucial parameter for understanding fire behavior. Smoke plays a central role in fire dynamics because it is often the source of much of the thermal radiation generated by a fire which contributes to flame spread and ultimately flashover. Smoke also reduces visibility and irritates the eyes of people trying to escape a fire, contributing to death and injury. Smoke damage represents a major property loss mechanism in fires and is particularly harmful to modern solid-state electronic circuits.

Despite the importance of smoke yield in fires, it has traditionally not been measured during fire tests. Previous measurement approaches involved collecting samples on filters while monitoring the total flow rate of combustion gases and weighing the amount of particulate collected. This approach is tedious and expensive. Light extinction has been used as a qualitative measure of the tendency of a fuel to generate smoke. For instance, light extinction measurements are often recorded during cone calorimeter tests. Until very recently, these measurements had provided primarily qualitative data since the specific extinction coefficient for smoke required to relate the observed light extinction to the smoke mass concentration had not been available.

Recently, Mulholland and Croarkin[9] have demonstrated that values of the specific extinction coefficient for smoke, σ_s, are nearly constant for a wide range of fuels when burned under fully ventilated conditions. A statistical analysis based on a number of measurements performed in different laboratories yielded $\sigma_s = 8.7\ m^2/g$ for a wavelength of 632.8 nm with an uncertainty interval of $\pm$ 1.1 m^2/g at the 95% confidence level. This finding, in combination with Bouguer's Law, allows the ratio of the transmitted (I) and incident intensities (I_o) to be related to the mass concentration of smoke, M_s, the path length through the smoke, L, and σ_s via the expression

$$\frac{I}{I_0} = \exp(-\sigma_s M_s L) \quad . \qquad (1)$$

When L is known, M_s can now be determined from a light extinction measurement, and, when the volume flow rate within the duct, $\dot{V}$, is also measured, the mass generation rate of smoke can also be determined. If the mass burning rate for the fuel, $\dot{m}_f$, is measured independently, the smoke yield, ϵ, over a period of time, t, can be calculated as

$$\varepsilon = \frac{\int \dot{V} M_s dt}{\int \dot{m}_f dt} \quad . \qquad (2)$$

This approach for measuring the smoke yield was implemented in the furniture calorimeter. A focus of the effort was to develop an optical system capable of accurate extinction measurements. The criteria required for accurate smoke extinction measurements were identified by Putorti[10] based on previous work at NIST and information available in the literature and included such parameters as the required sensitivity and noise levels. A system was then designed and built at NIST to meet these specifications.

Figure 1 shows a schematic for the optical system. The major components are a He-Ne laser with power stabilizer, a silicon photodiode detector and associated optics to minimize the effect of beam movement, purge tubes to prevent smoke deposition on the windows and to minimize forward scattered light reaching the detector, and both lateral and rotational positioning equipment for alignment of the laser beam and detector. Great care was taken to ensure that both the laser and silicon photodiode were sufficiently stable to allow a single-beam extinction measurement to be recorded over a twenty minute period. During the course of an experiment the temperature within the exhaust duct of the furniture calorimeter where the measurements are made increases, and the duct tends to expand somewhat. The expansion and contraction change the pathlength and, unless accounted for, can also result in misalignment of the optical system.

These and other effects were accounted for during the design and assembly of the smoke meter system. Commercial components were used, and the total cost for components and machining was less than $10,000.

A number of experimental tests of the new system were performed in order to characterize its performance and to demonstrate its ability to record smoke mass concentrations, generation rates, and yields with quantified uncertainties. These tests included monitoring the laser intensity during burning of natural gas, a low smoke fuel, in order to test the thermal stability of the experimental system; simulating soot absorption by the addition of neutral density filters spanning the expected absorption range; and measurements of extinction for repeated 50 kW, 200 kW, and 400 kW propane fires (a moderately smoky fuel) and more sooty pool fires burning on 50 cm-diameter pans containing either heptane, a 50%/50% mixture of heptane/toluene, or toluene. The smoke yield increases in the order heptane, 50%/50% mixture of heptane/toluene , and toluene for the liquid fuels.

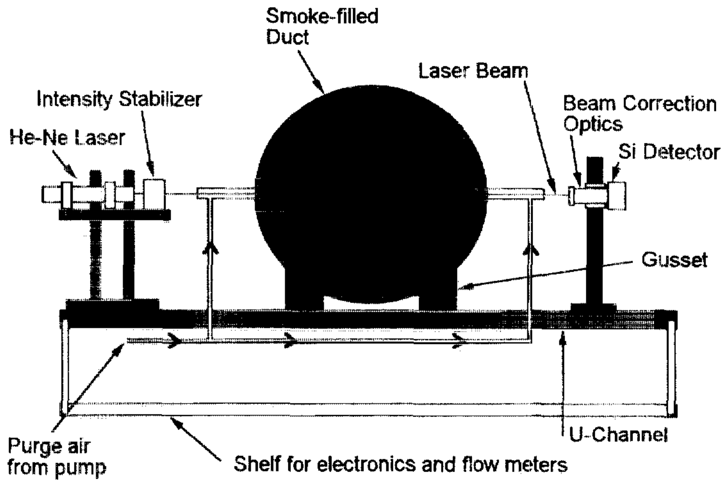

Figure 1. Overall schematic of smoke concentration meter.

During a fire the mass burning rate of the fuel was monitored so that it was possible to calculate the smoke yield. Figure 2 compares the mass flow rate of smoke in the duct with the fuel burning rate for one of the heptane fires. During these measurements the smoke yield from the heptane fire was measured to be 0.0129, which is within 7% of an earlier measurement for the same size fire using the smoke-collection method.[11] The coefficient of variation, defined as the standard deviation normalized by the average value, for repeated measurements of smoke yield was determined for each fire type. Values ranged from 0.01 to 0.11, with the highest values found for the smallest propane fires. The smoke yield was found to vary with propane fire size, decreasing from 0.0106 to 0.0052 over the range of heat release rates tested. The measured smoke yield for the toluene fires indicated that roughly 10% of the fuel mass appeared as smoke.

A detailed propagation of uncertainty analysis was performed for the smoke yield measurements. Such factors as the measured coefficient of variation and uncertainties in the specific extinction coefficient, fuel flow rates, smoke profile within the duct, and smoke deposition on the duct walls were considered in order to determine the overall uncertainty in the measurements. Including a coverage factor of 2 resulted in a relative uncertainty of 0.21 with a 95% confidence level.

To summarize, this work has significantly extended the usefulness of smoke extinction measurements in real-scale fire tests by developing an approach for quantifying the smoke mass concentration, and, when additional information is available, allowing calculation of the mass flow rate of smoke and smoke yield. A rigorous uncertainty analysis has provided a valid measure of the uncertainty associated with the measurements. The findings have been submitted for publication.[12]

5. Next Steps

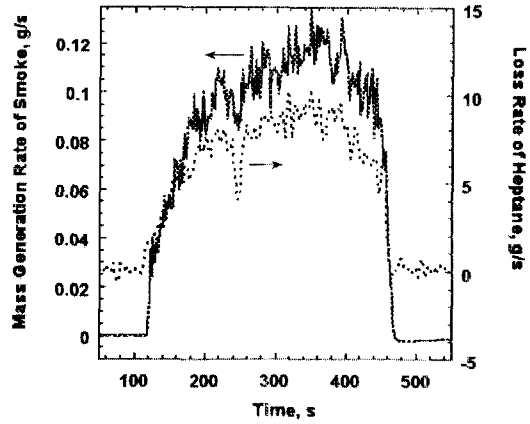

Figure 2. Mass generation rate of smoke and mass loss rate of fuel for 50 cm diameter heptane pool fire.

Much of the work summarized here is still in progress. Reports are being completed which describe the thermocouple results. An expert system will be developed to allow estimates for uncertainties in gas temperature measurements in real-scale fire tests. An operators manual for the new smoke meter is being prepared. The studies on heat-release rate and heat-flux measurements are continuing. Final reports will be prepared for each. One additional large-scale fire diagnostic in current use is to be selected for investigation during the project. A decision, based on written input, on whether or not near-infrared diode laser absorption offers a viable approach for measurement of molecular concentrations in fire environments will be available by summer. Based on this report, a decision will be made on whether or not to proceed with further development.

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